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Computer Code for Intraply Hybrid Composite Design

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C. C. Chamis and J. H. Sinclair
Lewis Research Center
Cleveland, Ohio

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New Orleans, Louisiana, January 27-29, 1981

NASA

COMPUTER CODE FOR INTRAPLY HYBRID COMPOSITE DESIGN

C. C. Chamis and J. H. Sinclair

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A computer program has been developed and is described herein for intraply hybrid composite design (INHYD). The program includes several composite micromechanics theories, intraply hybrid composite theories and a hygrothermomechanical theory. These theories provide INHYD with considerable flexibility and capability which the user can exercise through several available options. Key features and capabilities of INHYD are illustrated through selected samples.

INTRODUCTION

Intraply hybrid composites generally have two kinds of fibers embedded in the matrix. They have evolved as a structural material as a logical sequel to conventional composites and to interply hybrid composites. Intraply hybrid composites have unique features that can be used to meet diverse and competing design requirements in a more cost-effective way than either advanced or conventional composites. Some of the specific advantages of intraply hybrids over the constituent composites are balanced strength and stiffness, balanced bending and membrane mechanical properties, balanced thermal distortion stability, reduced weight and/or cost, improved fatigue resistance, reduced notch sensitivity, improved fracture toughness and/or crack-arresting properties, and improved impact resistance. By using intraply hybrids, the designer can obtain a viable compromise between mechanical properties and cost to meet specified design requirements for aerospace structures.

The mechanical behavior of intraply hybrids has been investigated at Lewis Research Center theoretically and experimentally (refs. 1 to 3). The theoretical methods and equations described in these references together with those for hygrothermal effects (ref. 4) have been integrated into a computer code for predicting hygral, thermal and mechanical properties of, and thereby, designing intraply hybrid composites. This code is identified as INHYD for INtraply HYbrid-composite Design. The objective of this paper is to describe INHYD with respect to theory, equations, input, output and its various options.

The capability and various options of the program are briefly described. Typical input for INHYD includes: fiber and resin properties or composite properties, volume ratios of the primary and secondary fibers, glass transition temperature of the resin, moisture, cure and use temperature. Typical output includes: moisture expansion coefficient, thermal expansion coefficients, moduli and strengths (in-plane and flexural). Selected samples of input and output are included to illustrate the flexibility and capability of INHYD. Also, the planned extensions and couplings with inte- grated computer programs are briefly discussed.

The complete documentation of INHYD with compiled listing, user instructions, and sample cases for each option will be available through

COSMIC - Computer Software Management and Information Center, Suite 112, Barrow Hall, Athens, Georgia 30602.

INTRAPLY HBYRID GEOMETRY AND DEFINITIONS

The generic geometry of intraply hybrids included in INHYD is shown schematically in figure 1. The features to be noted in this figure are as follows:

1. The schematic shows an eight ply unidirectional intraply hybrid. Each ply consists of primary composite (blank) and secondary composite (cross-hatched).
2. The location of the secondary composite is regular and staggered through the thickness of the intraply hybrid.
3. The coordinate reference axes are 1, 2, and 3 where 1 is taken parallel to the fiber direction, 2 is taken transverse to the fiber direction and 3 through the thickness. These coordinate axes will be called the material axes. All properties to be discussed in subsequent sections are defined with numerical subscripts corresponding to material axes.

It is clear from figure 1 that an intraply hybrid is made by laying tapes (tows) of primary composite and tapes (tows) of secondary composite in a definite manner in order to obtain the desired volume ratios of each. For purposes of identification, the primary composite in the hybrid is the one which constitutes the largest volume ratio. This imposes no limitations on either the capability or flexibility of INHYD. Another way to view an intraply hybrid is the one in which the constituent composites are uniformly dispersed in a typical cross-sectional area.

THEORIES INCLUDED IN INHYD

The theories programmed in INHYD have been reported previously and include (1) rule of mixtures (ref. 1), (2) micromechanics equations for hygrothermal effects (ref. 2) and (3) intraply hybrid composite micromechanics (ref. 4). Also, several equations have been programmed for predicting flexural strength and through the thickness shear as will be described later. These theories consist of equations which predict intraply hybrid composite properties based on constituent composite (primary and secondary) properties. The constituent composite properties may in turn be predicted by micromechanics equations using fiber and matrix properties. Essential features of these theories are summarized below. The detailed derivations, equations and justifications are found in the original references.

The rule of mixtures equations have the following form (ref. 1)

$$P_{HC} = V_{PC}P_{PC} + V_{SC}P_{SC} \tag{1}$$

where P denotes property and V volume ratio. The subscript HC denotes hybrid composite; PC, primary composite; and SC, secondary composite. Any property of the intraply hybrid composite can be predicted by using equation (1) when the properties of the primary and secondary composites have been specified. Equation (1), though of simple form, <u>does</u> satisfy the three principles of mechanics: force equilibrium, strain compatibility, and stress-strain relationships. Equation (1) predicts values which are in good agreement with measured data (ref. 1) and with other more sophisticated theories (ref. 2). Equation (1) is programmed as two subroutines in INHYD:

one for the primary composite and one for the secondary composite. These subroutines require input of constituent composite properties. The individual properties required are summarized in later sections.

The micromechanics equations from reference 4 are programmed in INHYD for predicting composite properties using fiber and matrix properties and accounting for hygrothermal effects. These equations are also programmed in two different subroutines: one for predicting primary composite properties and one for predicting secondary composite properties. Calls to these subroutines require inputs of fiber and matrix properties, fiber volume ratio, void volume ratio, use temperature and moisture. The individual properties needed are described later.

The intraply hybrid composite micromechanics equations from reference 2 are programmed in INHYD. Three subroutines are used. One each for the primary and the secondary constituent composites and one which combines these two into an intraply hybrid. The first two subroutines require fiber and matrix properties while the third requires the primary and secondary composite properties predicted by the first two.

The properties predicted by all of the above theories are those which result from uniform response (due to moisture, temperature or stress) variation through the thickness of the intraply hybrid. Properties resulting from nonuniform response, variation through thickness such as flexural strength and short beam shear strength are considered in the next section.

FLEXURAL PROPERTIES

The equations programmed for flexural properties in INHYD are for flexural strength along the 1-direction, along the 2-direction, and the accompanying shear strength in 1-3 plane (short beam shear) in figure 1. Four different equations are programmed for flexural strengths. The equations have not been reported previously. The equations are readily derivable using the well known simple beam theory and assumed stress variations through the beam thickness at fracture (fig. 3). The four equations included in INHYD were derived by assuming: (1) bilinear stress distribution; (2) parabolic stress distribution; (3) linear rectangular stress variation; and (4) rectangular stress distribution (fig. 3). All these distributions are possible in intraply hybrid composites depending on their constituents. The selections of a specific equation requires user interaction based on measured data correlation. The default option in INHYD is the parabolic stress distribution. All four equations are programmed in two different subroutines,
one for the primary composite and one for the secondary composite. The corresponding flexural strengths for the intraply hybrid are calculated in the same subroutine for intraply hybrid micromechanics.

The equation for the through-the-thickness shear strength in the 1-3 plane is derived by assuming parabolic shear stress variation. The integral of this parabolic variation is equated to uniform inplane shear to obtain the desired equation. This results in the simple relationship: The through-the-thickness shear (short beam shear) is equal to 1.5 times the corresponding in-plane shear strength. The short beam shear strength of the intraply hybrid is calculated in the same subroutine as the flexural strength. The equation for predicting the short-beam-shear strength in the 2-3 plane (fig. 1) is similar, but it is not programmed in INHYD. The reason that it is not programmed is that experimental data indicate that specimens tested for this shear fail invariably by transverse flexure.

INHYD COMPUTER PROGRAM STRUCTURE

The logic flow of the INHYD computer program is illustrated schematically in figure 2. The theoretical functions of the program are enclosed with doubled lines. The input, intermediate output, and final output are enclosed with single lines. Typical final uses of the output are enclosed with interrupted lines. The various micromechanics theories and requisite subroutine described previously are included in the first double-line block. Those for predicting the intraply hybrid properties are included in the second double-line block. The user controls INHYD through the main subroutine by selecting combinations of the several available options. The options in INHYD are summarized in table I. It is clear from table I that combinations of options can be specified for theory, hybrid, input property sets and hygrothermal effects.

The input of INHYD is summarized in table II. A sample of user input data set is shown in table III when the intraply hybrid properties will be predicted using fiber and matrix properties. The first set of Booleans are the options for input read-in formats and for environmental effects. The first line of data is the secondary composite volume ratio. The second set of Booleans specify the composite micromechanics subroutines to be used. The alphanumerics describe the primary composite system. The next (third) set of Booleans define the fiber properties that will be read in. This set of Booleans is followed by the primary composite fiber properties: moduli, Poisson's ratios, thermal expansion coefficients, density, number of fibers per end, fiber diameter, heat capacity, heat conductivities, and tensile and compressive strengths. The alphanumeric card following the fiber properties describes the primary composite matrix and the environmental conditions. The next (fourth) set of Booleans specify the matrix properties to be read in. These matrix properties are moduli, moisture expansion coefficient per percent of moisture, thermal expansion coefficients, heat capacity, thermal conductivity, strengths (tensile, compressive and shear), moisture diffusivities, glass transition temperatures, reference temperature, moisture content, volume ratios (fiber, matrix, void). The data following are the input data needed for the fiber and matrix in the secondary composite. The format for these data is similar to those (one for one correspondence) for the primary composite.

Formatted output (compiled data) of the input data for the primary composite fiber properties is shown in table IV and in table V for the matrix. In these tables the Booleans for the various program options, the fiber and matrix types, the volume ratios and the constituent properties (with the corresponding program name) are displayed. The reader can readily match corresponding values from the user input data (table III) and the compiled data (tables IV and V).

INHYD program output features are summarized in table VI. A sample output for the predicted primary composite properties (using the input data tables IV and V) is illustrated in table VII. The volume ratio values and 37 properties are listed in this table. The various properties are identified by both name and assigned variable used in the program. Note the flexural properties, lines 29 to 34. Note also the ply thickness (line 35), the interply thickness (line 36) and the interfiber spacing (line 37). The format for the outputs of the secondary composite and for the intraply hybrid are similar to that for the primary (table VII).

INHYD PROGRAM CAPABILITY-ILLUSTRATED EXAMPLES

The INHYD program capability and flexibility is illustrated, in part, with typical illustrative examples. The effects of hybridization on selected properties are summarized in table VIII for 70° F, dry environmental conditions. The properties shown in this table were predicted using the user input data in table III. Corresponding properties for the primary, the secondary, and the intraply hybrid composite are summarized. Corresponding properties for the primary composite are the same as those in table VII.

The thermal degradation, due to elevated temperature, in the properties of two intraply hybrids (AS/E//S-G/E and (AS/E//KEV/E) is illustrated in table IX. It is instructive to note in this table that the thermal degradation is insignificant in longitudinal properties (except longitudinal compressive strength). However, the thermal degradation is considerable (about 30 percent) for transverse and shear properties and for longitudinal compressive strength.

The hygrothermal degradation in the properties of the AS/E//S-G/E intraply hybrid is illustrated in table X. The hygrothermal environments are 70° F with 1-percent moisture and 250° F with 1-percent moisture. Again, the hygrothermal degradation is insignificant for the longitudinal properties, except for the longitudinal compressive strength. On the other hand the 1-percent moisture degrades the transverse and shear properties and the longitudinal compressive strength about 10 percent for the 70° F case and about 30 percent for the 250° F case.

INHYD EXTENSIONS AND COUPLING

The properties predicted by INHYD described previously constitute only the first part of INHYD. The program can be readily extended to predict other properties of intraply hybrids such as impact resistance and fatigue. In addition it can be made a part of or coupled with integrated programs for special and/or general structural analysis. The near future planned extensions and couplings with other programs are summarized in table XI. The theory for impact resistance in reference 5, will be used. The theory for fatigue resistance is presently under development and will be reported in the ASTM 6th Conference on Composite Materials: Testing and Design, May 1981. INHYD will be coupled with an in-house laminate analysis code (MFCA, ref. 6). It will also be coupled with three integrated computer programs under in-house development: CODSTRAN - Composite Durability Structural Analysis (ref. 7); COBSTRAN - Composite Blade Structural Analysis (ref. 8); and CISTRAN Composite Impact Structural Analysis (ref. 9).

CONCLUSIONS

A computer program INHYD has been developed to predict the properties of unidirectional intraply hybrid composites and, therefore, assist in the design of these hybrids. Several composite micromechanics and intraply hybrid theories, and a hygrothermal mechanical theory in INHYD provide the program with considerable flexibility which the user exercises through combinations of options. These options control the input data, fiber/matrix, unidirectional composite or combinations, the output and the theory. Selected samples illustrate key features and capabilities INHYD. INHYD provides the designer/analyst with a convenient analytical means to investigate

several intraply hybrids during the preliminary design phases. INHYD can also be used to guide, and therefore keep to a minimum, required characterization of intraply hybrids.

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TABLE I. - PROGRAM OPTIONS

Selects theory to be used

Hybrid or conventional composite

Types of property inputs

- Composite properties
- Constituent properties
- Combinations

Hygrothermal effects

TABLE II. - PROGRAM INPUT

User options

Constituent properties (fiber, matrix) or properties of primary and secondary composites or combinations

Fiber volume ratio, void volume ratio

Primary composite ratio, secondary composite ratio

Temperature, moisture

TABLE III. - USER INPUT DATA

```
F T T T
   0.20E+00
  T
  T
  T
  T
 AS GRAPHITE FIBER
  F
  T
  F
  F
     32.E+06        2.E+06         2.E+06         1.E+06            .2
         .25      -.54E-06       5.4E-06           .063         1.E+04
     3.E-04            .17         500.0           58.0           58.0
   400.E+03       400.E+03
 EPOXY MATRIX - 3501-5 - 250F - DRY
  F
  F
  F
  T
    .46E+06      .1643E+06            .4        32.E-06       .443E-01
        .25           1.25       6.0E+03       36.3E+03        7.E+03
        0.4        2.0E-04
      460.0          394.0           0.0
        .55            .45           0.0
  F
 S-GLASS FIBER
  F
  T
  F
  F
    12.4E+06      12.4E+06      5.17E+06       5.17E+06             .2
         .20       2.8E-06       2.9E-06            .09           204.
     3.6E-04           .17           7.5            7.5            7.5
     .36E+06        .2E+06
 EPOXY MATRIX - 3501-5 - 250F - DRY
```

TABLE IV. - COMPILED DATA
PART I - FIBER

```
VSC=  .200+00
MRUL=     T      PHTMP=     T      SHTMP=     T
PRIN=     T

COMP=     F      FIBER=     T      MAT=     F      TMAT=
```

PRIMARY FIBER PROPERTIES
AS GRAPHITE FIBER - 250F -

1	ELASTIC MODULI	EFP1	.3200+08
2		EFP2	.2000+07
3	SHEAR MODULI	GFP12	.2000+07
4		GFP23	.1000+07
5	POISSON'S RATIO	NUFP12	.2000+00
6		NUFP23	.2500+00
7	THERM. EXP. COEF.	CTEFP1	.5600-06
8		CTEFP2	5600-05
9	DENSITY	RHOFP	.6300-01
10	NO. OF FIBERS/END	NFP	.1000+05
11	FIBER DIAMETER	DIFP	.3000-03
12	HEAT CAPACITY	CFPC	.1700+00
13	HEAT CONDUCTIVITY	KFP1	.5800+03
14		KFP2	.5800+02
15		KFP3	.5800+02
16	STRENGTHS	SFPT	.4000+06
17		SFPC	.4000+06

TABLE V. - COMPILED DATA
PART II - MATRIX

```
COMP=     F      FIBER=     F      MAT=     F      TMAT=     T
```

PRIMARY MATRIX PROPERTIES
EPOXY MATRIX - 3501-5 - 250F - DRY

```
TGDR=     .4600+03        T=     .3940+03        M=     .0000
```

ORIGINAL MATRIX PROPERTIES

1	ELASTIC MODULUS	EMP	.4600+06
2	SHEAR MODULUS	GMP	.1643+06
3	POISSON'S RATIO	NUMP	.4000+00
4	THERM. EXP. COEF.	CTEMP	.3200-04
5	DENSITY	RHOMP	.4430-01
6	HEAT CAPACITY	CMPC	.2500+00
7	HEAT CONDUCTIVITY	KMP	.1250+01
8	STRENGTHS	SMPT	.6800+04
9		SMPC	.3630+05
10		SMPS	.7000+04
11	MOISTURE COEF.	BTAMP	.4000+00
12	DIFFUSIVITY	DIFMP	.2000-03

TABLE VI. - OUTPUT

- PRIMARY, SECONDARY COMPOSITE PROPERTIES

  3 EACH, ELASTIC MODULI, SHEAR MODULI, POISSONS' RATIOS, THERM. EXP. COEF.

  DENSITY, HEAT CAPACITY

  3 HEAT CONDUCTIVITIES, 5 IN-PLANE STRENGTHS

  3 EACH, MOISTURE DIFFUSIVITIES AND MOISTURE EXPANSION COEFS.

  2 FLEXURAL MODULI

  4 THRU-THE-THICKNESS STRENGTHS

  PLY THICKNESS, INTERPLY THICKNESS, INTERFIBER SPACING

- INTRAPLY HYBRID COMPOSITE PROPERTIES

  SAME AS ABOVE EXCEPT FOR LAST LINE PLUS

  COMPOSITE FIBER VOLUME RATIO

TABLE VII. - TYPICAL COMPUTER OUTPUT OF INTRAPLY HYBRID PROPERTIES

PRIMARY COMPOSITE PROPERTIES

VFP= .5500+00 VMP= .4500+00 VVP= .0000

1	ELASTIC MODULI	EPC1	.1780+08
2		EPC2	.1034+07
3		EPC3	.1034+07
4	SHEAR MODULI	GPC12	.4902+06
5		GPC23	.4140+06
6		GPC13	.4902+06
7	POISSON'S RATIO	NUPC12	.2900+00
8		NUPC23	.2445+00
9		NUPC13	.2900+00
10	THERM. EXP. COEF.	CTEPC1	-.1016-06
11		CTEPC2	.1640-04
12		CTEPC3	.1640-04
13	DENSITY	RHOPC	.5450-01
14	HEAT CAPACITY	CPC	.2040+00
15	HEAT CONDUCTIVITY	KPC1	.3196+03
16		KPC2	.3916+01
17		KPC3	.3916+01
18	STRENGTHS	SPC1T	.2224+06
19		SPC1C	.1713+06
20		SPC2T	.6407+04
21		SPC2C	.3420+05
22		SPC12	.6895+04
23	MOIST. DIFFUSIVITY	DPC1	.9000-04
24		DPC2	.5140-04
25		DPC3	.5140-04
26	MOIST. EXP. COEF.	BTAPC1	.4304-02
27		BTAPC2	.1131+00
28		BTAPC3	.1131+00
29	FLEXURAL MODULI	EPC1F	.1780+08
30		EPC2F	.1034+07
31	STRENGTHS	SPC23	.6595+04
32		SPC1F	.2410+06
33		SPC2F	.1349+05
34		SPCSB	.9093+04
35	PLY THICKNESS	TPC	.5000-02
36	INTERPLY THICKNESS	PLPC	.5050-04
37	INTERFIBER SPACING	PLPCS	.5853-04

TABLE VIII. - EFFECT OF HYBRIDIZATION ON COMPOSITE PROPERTIES (DRY, 70° F)

	AS/E PRIMARY COMPOSITE 80%	S-G/E SECONDARY COMPOSITE 20%	INTRAPLY HYBRID COMPOSITE AS/E//S-G/E 80/20
ELASTIC MODULI	.1780+08 .1034+07	.7015+07 .1524+07	.1564+08 .1132+07
SHEAR MODULI	.4902+06 .4148+06	.5517+06 .5517+06	.5025+06 .4422+06
POISSON'S RATIO	.2900+00	.2900+00	.2900+00
STRENGTHS	.2224+06 .1712+06 .6407+04 .3420+05 .6595+04	.2017+06 .1448+06 .6407+04 .3420+05 .6595+04	.2187+06 .1659+06 .6407+04 .3420+05 .6595+04
FLEXURAL MODULI	.1780+08 .1034+07	.7015+07 .1524+07	.1564+08 .1132+07

TABLE IX. - ILLUSTRATION OF THERMAL DEGRADATION IN INTRAPLY HYBRIDS

INTRAPLY HYBRID COMPOSITE PROPERTY		AS/E//S-G/E,80/20		AS/E//KEV/E,80/20	
		70 F	250 F	70 F	250 F
ELASTIC MODULI	EMC1 EMC2	.1564+08 .1132+07	.1557+08 .8067+06	.1670+08 .9365+06	.1662+08 .6995+06
SHEAR MODULI	GMC12 GMC23	.5025+06 .4422+06	.3368+06 .3077+06	.4504+06 .3715+06	.3104+06 .2693+06
POISSON'S RATIO	NUMC12	.2900+00	.2900+00	.3065+00	.3065+00
STRENGTHS	SMC1T SMC1C SMC2T SMC2C SMC12	.2187+06 .1659+06 .6407+04 .3420+05 .6595+04	.2175+06 .1432+06 .4040+04 .2157+05 .4159+04	.2227+06 .1531+06 .6407+04 .3420+05 .6595+04	.2217+06 .1306+06 .4040+04 .2157+05 .4159+04
FLEXURAL MODULI	EMC1F EMC2F	.1564+08 .1132+07	.1557+08 .8067+06	.1670+08 .9365+06	.1662+08 .6995+06

TABLE X. - ILLUSTRATION OF HYGROTHERMAL DEGRADATION IN INTRAPLY HYBRID (AS/E//S-G/E, 80/20)

INTRAPLY HYBRID COMPOSITE PROPERTY		70 DEG. F		250 DEG. F	
		DRY	1.0% MOISTURE	DRY	1.0% MOISTURE
ELASTIC MODULI	EMC1	.1564+08	.1562+08	.1557+08	.1552+08
	EMC2	.1132+07	.1033+07	.8067+06	.5713+06
SHEAR MODULI	GMC12	.5025+06	.4500+06	.3368+06	.2279+06
	GMC23	.4422+06	.4006+06	.3077+06	.2140+06
POISSON'S RATIO	NUMC12	.2900+00	.2900+00	.2900+00	.2900+00
STRENGTHS	SMC1T	.2187+06	.2183+06	.2175+06	.2169+06
	SMC1C	.1659+06	.1584+06	.1432+06	.1297+06
	SMC2T	.6407+04	.5626+04	.4040+04	.2631+04
	SMC2C	.3420+05	.3003+05	.2157+05	.1405+05
	SMC12	.6595+04	.5791+04	.4159+04	.2709+04
FLEXURAL MODULI	EMC1F	.1564+08	.1562+08	.1557+08	.1552+08
	EMC2F	.1132+07	.1033+07	.8067+06	.5713+06

TABLE XI. - PLANNED EXTENSION

- PROGRAM AND DOCUMENTATION WILL BE MADE AVAILABLE TO THE PUBLIC THROUGH COSMIC
- EXTEND PROGRAM TO DETERMINE IMPACT RESISTANCE, DEFECT PROPAGATION, AND FATIGUE RESISTANCE OF UNIDIRECTIONAL INTRAPLY HYBRIDS
- COUPLE WITH MULTILAYERED FILAMENTARY LAMINATE ANALYSIS (MFCA)
- COUPLE INHYD WITH:
  - CODSTRAN - COMPOSITE DURABILITY STRUCTURAL ANALYSIS
  - COBSTRAN - COMPOSITE BLADE STRUCTURAL ANALYSIS
  - CISTRAN - COMPOSITE IMPACT STRUCTURAL ANALYSIS
- CONVERT PROGRAM TO IBM 370/3033

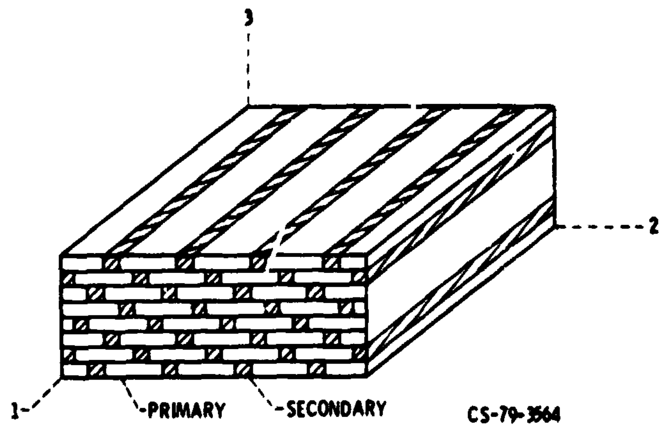

Figure 1. - Schematic of unidirectional intraply hybrid composite.

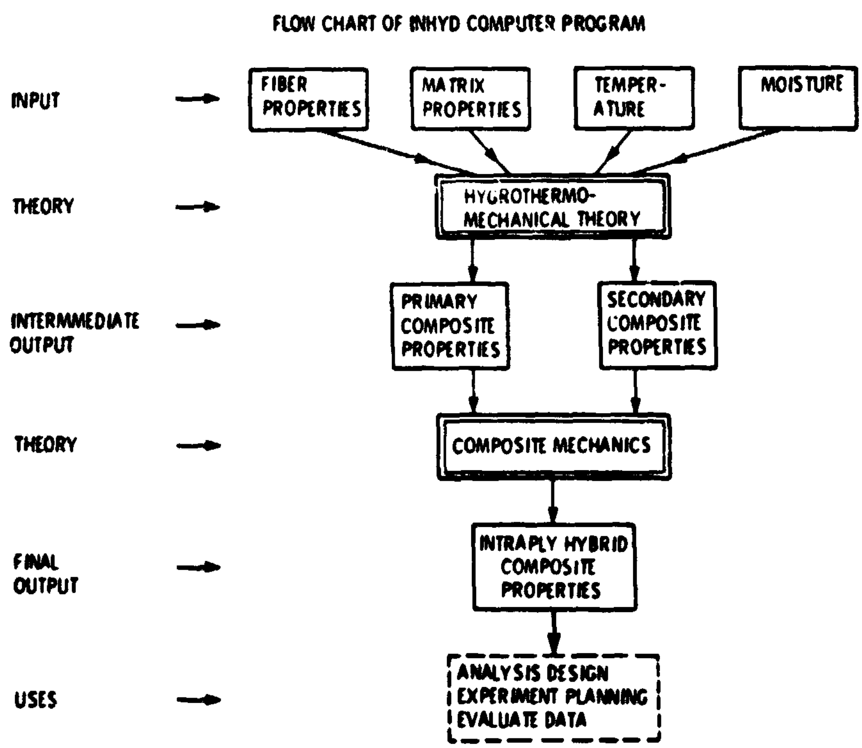

Figure 2. - Flow chart of inhyd computer program.

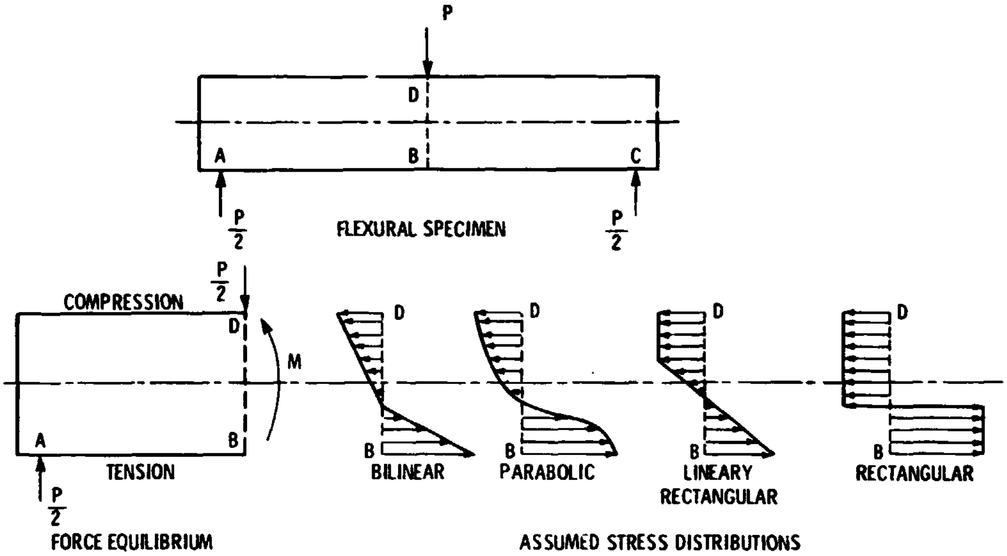

Figure 3. - Geometry, force and stress distributions for estimating flexural strength.